COVER SHEET

Paper Number: **1828**

Title: **Non-destructive Evaluation of Bonds between Fiberglass Composite and Metal**

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ABSTRACT

To assess the integrity and reliability of an adhesive joint in an automotive composite component, several non-destructive evaluation (NDE) methodologies are correlated to lap shear bond strengths. A glass-fabric-reinforced composite structure was bonded to a metallic structure with a two-part epoxy adhesive. Samples were subsequently cut and tested in shear, and flaws were found in some areas. This study aims to develop a reliable and portable NDE system for service-level adhesive inspection in the automotive industry. The results of the experimental investigation using several NDE methods are presented and discussed.

Fiberglass-to-metal bonding is the ideal configuration for NDE via thermography using excitation with induction heating, due to the conductive metal and non-conductive glass-fiber-reinforced composites. Excitation can be either by a research-grade induction heater of highly defined frequency and intensity, or by a service-level heater, such as would be used for sealing windshields in a body shop. The thermographs thus produced can be captured via a high-resolution infrared camera, with principal component analysis and 2D spatial Laplacian processing. Alternatively, the thermographs can be captured by low resolution thermochromic microencapsulated liquid crystal film imaging, which needs no post-processing and can be very inexpensive. These samples were also examined with phased-array ultrasound. The NDE methods are compared to the lap shear values and to each other for approximate cost, accuracy, and time and level of expertise needed.

INTRODUCTION

With new federal regulations on vehicle fuel economy, composite materials with high mechanical properties and corrosion resistance are playing an increasingly significant role in the automotive industry via light-weight vehicle development. Adhesive bonding has been successfully implemented for bonding between metal parts and composite parts for structural and non-structural applications. The adhesive coverage on complex automotive parts like hood closures could be affected by a number of issues during manufacturing, such as air bubble in the adhesive dispenser equipment lines, clogged dispenser nozzles, equipment out of calibration, or just sloppy application. The currently available method for checking adhesive application in automotive manufacturing is applying enough adhesive that there is squeeze-out from both sides. However, for those regions which do not have full coverage of the adhesive, teardown may be required to confirm the width of the adhesive bead. Most applications require a bead width between 15 to 25mm. The evaluation of adhesive distribution after the assembly line set up and maintenance also relies on part teardown and visual inspection, which is quite costly and time consuming.

In order to establish a reliable adhesive bonding process in manufacturing environments as part of quality assurance, especially on load-critical primary structure, a robust and portable non-destructive evaluation (NDE) technology is highly recommended to confirm the width and shape of the adhesive bead for large scale automotive components.

In the aerospace industry, conventional ultrasound and active thermography NDE technologies with fairly high accuracy and sensitivity have been well established via significant research activities [1, 2]. These can provide very accurate dimensional measurements of the adhesive bead. Meanwhile, low cost, short inspection time and easy data interpretation with no compromise in performance are desired attributes for selecting adhesive joint inspection systems in automotive manufacturing.

High frequency focused immersion ultrasound could provide high spatial resolution and bond-line characterization [3]. However, it requires precise mechanical scanners and a long time to scan large scale automotive parts, such that it would be very difficult to implement this technology in plants. Phased array ultrasound or single element transducer UT could be a good potential technique for field application [4]. It requires direct contact with the part via a couplant material such as ultrasonic gel or water. In this paper, we have investigated a linear array ultrasound system in pulse-echo mode for metal-to-fiberglass adhesively-bonded joints. The samples have been scanned from both metal side and composites side, to simulate only one-side accessibility of a part due to the shape of the probe or the part's complex geometry.

Active thermography generally utilizes various thermal stimulation techniques and an IR camera to capture thermal discontinuities, which were caused by the internal flaws or thickness variations in the part. The materials' thermal properties, such as thermal conductivity and diffusivity, determine the applicability of these techniques. In this paper, we will focus on pulse and induction heating thermography on a metal-to-fiberglass bonded structural part. Both high resolution IR cameras and a low resolution microencapsulated liquid crystal film have been evaluated.

MATERIAL SYSTEM AND TESTS

Composite Substrates and adhesive system

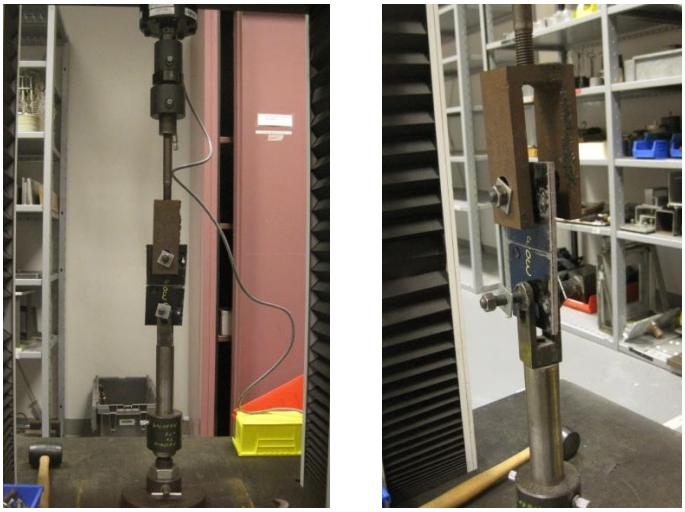
The composite substrate material was a coarse basket weave fiberglass (Fiberglass Industries 2454) made into a prepreg by Cytec, using a low volatile organic compound, hot melt vinyl ester resin from Reichold. The fiberglass prepreg is prefomed with a 7-ply, quasi-isotropic layup, transferred from the preforming bucks to the molding tool, and molded to 3.9 mm using closed-tool compression molding. The steel is DP800, 2 mm thick.

The bonding used an Ashland 7400 series urethane adhesive. Surfaces were scuffed, wiped with isopropyl alcohol, and bonded in fixtures at room temperature. Bonds are confirmed using a crowbar test on all samples.

Lap Shear Preparation and Testing

When a few of the samples undergoing the crowbar test showed poor results, a lap shear test was developed to quantify the bonding. The basis of the test was SAE J1525, but because of the geometry involved in the part, modifications in the sample geometry were necessary. The samples cut from the composites part were long rectangular or irregularly shaped pieces which included a composite-to-metal bond. Holes were drilled at either end of the rectangle to allow for mounting in a tensile test machine. On the composite side of the sample, a cut was made through the composite to the steel,

across the width of the sample. On the steel side of the sample, a similar cut was made through the metal to the composite 25 mm away from the first cut. This provided a bond area of 25 mm length which was effectively separated from the rest of the sample, which then acted as tabs. With these modifications, it was possible to quantify the bond strength. Figure 1 shows the test setup for the lap shear testing.



(a) (b)

Figure 1. (a) Load train setup for the lap shear testing. (b) Close-up of the sample fixturing.

NON DESTRUCTIVE EVALUATION METHODOLOGIES

Phased array ultrasound

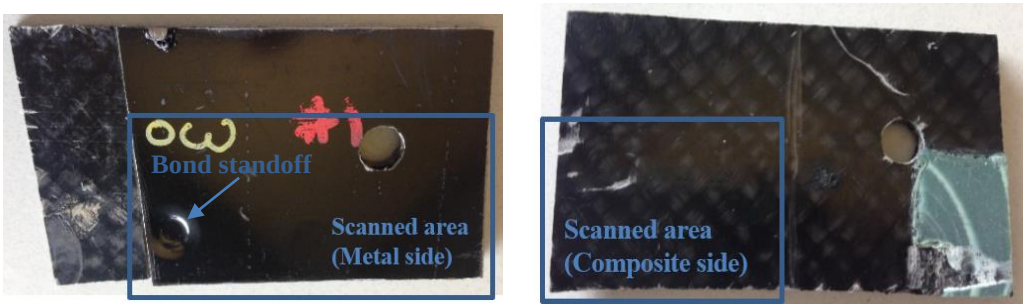
The accessibility of automotive components matter with any type of NDE, but particularly when using ultrasonic inspection with a linear-array probe. We scanned the flat areas of these parts from both the metal and the composite sides, focusing on the interface between the part and the adhesive. Scanning from the metal side was quite difficult due to the large impedance mismatch between the metal and adhesive layers. From the composite side, however, the nature of a fabric-reinforced composite dictates that there are several interfaces, not only between resin and fiber, but between layers of fabric. Any of these are prime locations for voids or delaminations, which will block the sound wave before it travels to the interface between composites and adhesive layer. In this paper, a MatrixEye™ system from Toshiba with SAFT (Synthetic Aperture Focusing Technique) which improves the S/N ratio and restores images from focusing distortion [5] was used. A 15MHz, 64-element linear array probe was used to scan the metal side, and a 5MHz, 64-element probe for the composites side. A wire encoder provides a maximum 1m scanning length. The measurement conditions are listed in Table I. for inspection from metal and composites sides, respectively. For this work, the 64 total elements have been arranged as 15-element per group and excited at a 0° incident angel. The sampling rate for generating the A-scan waveform is 40MHz.

Figure 2 shows one of the bonded samples from both the metal side and the composite side. This sample measures about 110mm by 60mm, and an area of about 38mm by 96mm was scanned after lap-shear testing. The metal substrate has a designed stand-off for controlling adhesive thickness.

TABLE I. MEASUREMENT CONDITIONS OF SYSTEM SETUP

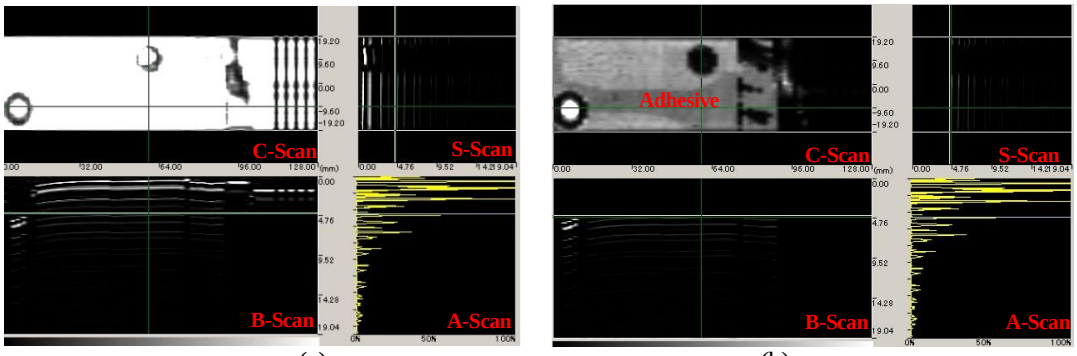
Scan Surface	Probe Frequency	Pitch of Array	Ultrasound Speed	Resolution			Pulse Width
				Index	Scan	Depth	
Metal	15MHz	0.6mm	5950m/s	0.6mm	2mm	0.0372mm	24ns
Fiberglass	5MHz	1mm	3000m/s	1mm	2mm	0.0375mm	24ns

Figure 3a shows a series of reverberations of the ultrasonic waves in the B-scan and S-scan, due to the high sound velocity in the metal. These reverberations overlap the echoes from the interfaces between the adhesive and composite substrate. Using appropriate filtering, we are able to deconvolute these interferences, allowing us to find the correct gates for the interfaces of metal-to-adhesive and adhesive-to-composite. To reduce the amplitude of the reverberations, the inverse filtration and subtraction algorithm on first two groups of echoes near the metal surface has been applied under HW+ (half wave positive) A-scan rectification. The effect of this can be seen in Figure 3b. The width of the adhesive bead, as measured in C-Scan image, is 7mm to 12mm in this sample.



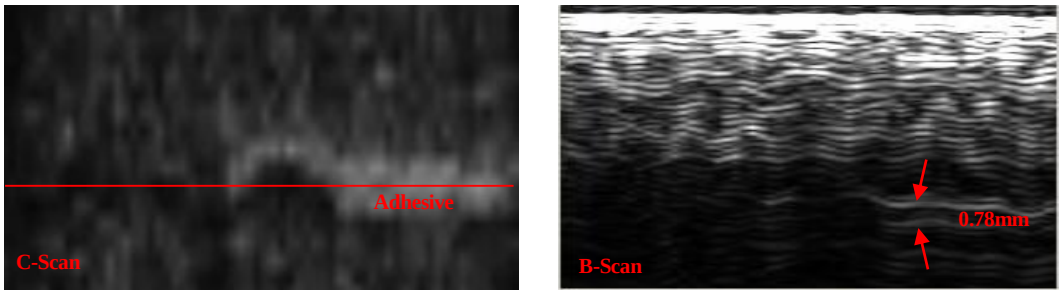
(a) (b)

Figure 2. The cut section #1 (a) Metal side and (b) Composites side from enclosure with stand-off on metal side and residual adhesive on composites side. Note that these samples were bonded on both sides, thus the residual adhesive on the composite side.



(a) (b)

Figure 3. Scan from metal side (a) before subtraction of reverberations and (b) after subtraction of reverberation



(a) (b)

Figure 4. Scan from composites side (a) C-scan and (b) B-scan

The ultrasonic scanned results from the composites side of the same sample is shown in Figure 4. Due to the residual adhesive on the surface and the size of linear array probe, the scanned area is 45mm by 65mm. The C-scan view in Figure 4a reveals the adhesive bead near the metal stand-off when the peak mode gate is set from the first interface (composites-to-adhesive) to the second interface (adhesive-to-metal). The B-scan in Figure 4b was captured along the red line in the C-scan. The adhesive thickness could be measured as 0.78mm between two echoes pointed out by red arrows.

Pulsed thermography

Pulse thermography is a contactless and full field NDE technique. It can quickly detect and qualitatively assess the structural defects underneath the surface. During short-pulsed thermal stimulation, the transient heat flow in the area with subsurface defects can be obstructed. The differences in the infrared radiation distribution between the areas with and without defects can be captured by an infrared camera. The data analyzing system will convert the measurement into a temperature vs. time map for further infrared image enhancement.

The Thermal Wave Imaging ThermoScope II IR system was used in this evaluation. The system consists of two high intensity xenon flash lamps, an infrared camera and a data acquisition system. An exposure time of about 4ms at a light intensity of about 9.6 kJ per flash was used as the heat source for the uniform illumination on the target surface. The infrared camera was equipped with a 13 mm lens and a 640 x 512 resolution InSb detector, with a snapshot Focal Plane Array for 3-5 um IR radiation and a 14-bit digital data output. Its frame rate can reach up to 30 frames per second (fps) at a resolution of 650 x 512 and up to 120 frames per second at a resolution of 320 x 256. In our case, the intensity of the flash lamps was set to 100% with a 30 fps camera frame rate for a 25-second data acquisition window. The distance from the sample to the IR camera was set at 220mm while the flash event occurred 200mm away from the sample surface. Since the thermal diffusivity in the metal are much higher than it in the composites, this technology is more applicable from composites side than from metal side for adhesive evaluation.

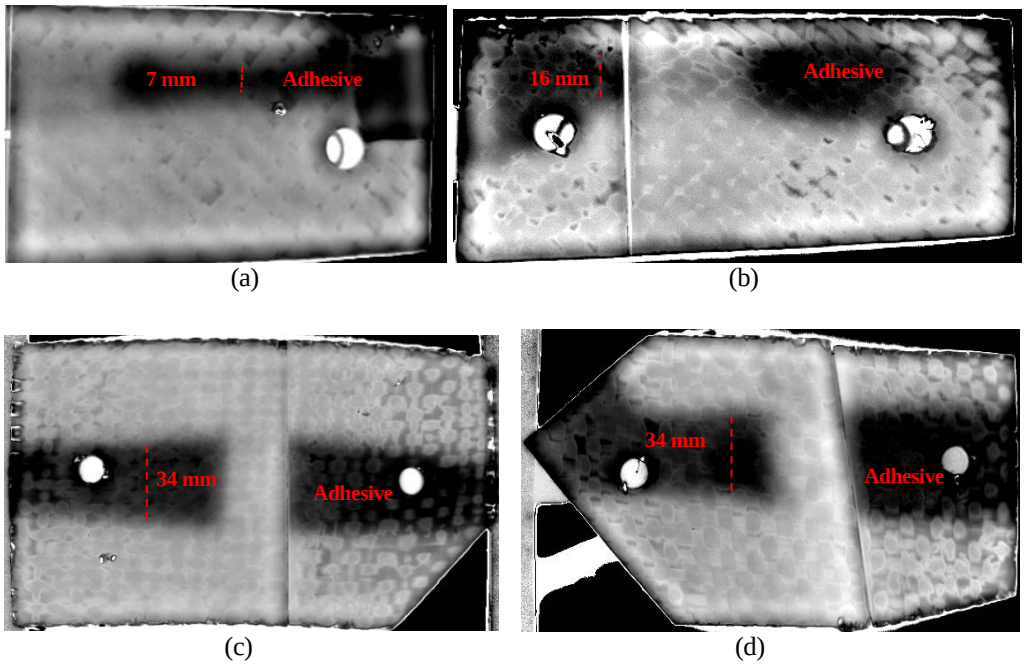


Figure 5. Pulsed thermography measurements. Cut-sections in Figure (a) cut section #1 and (b) cut section #2 are relatively low bond strengths with inconsistent and intermittent bond widths, as Figure (c) cut section #3 and (d) cut section #4 have higher bond strengths and more consistent coverage.

Representative images and measurements obtained from pulsed thermography of the adhesive bead are shown in Figure 5. The difference between bonded and non-bonded areas show clearly with this technique. The non-uniform distribution of adhesive beads seen in Figure 5(a) and (b) shows a width variation from 7mm to 16mm. This corresponds to relatively low lap-shear strengths of 5 MPa and 6 MPa. In contrast, Figure 5(c) and (d) show that the adhesive is distributed very uniformly, with measured adhesive width of 34 mm on the two different samples. These correlate with high lap-shear strengths of 19 MPa and 17 MPa on these two samples.

Eddy Current Heating

Because the composite of interest is bonded to a metallic substrate, it is possible to heat the substrate using eddy currents. For proof-of-concept, laboratory investigations, the heating system used is the ITS™ (Induction Thermography System) commercially available from QUEST Integrated, LLC. The ITS unit delivers up to 2 kW of RF energy in the 160-400 kHz range in a pulsed mode [6]. The resulting heat deposition in the material occurs very rapidly with heating times for these experiments lasting 5 to 10 seconds. Figure 6 shows a photograph of the ITS system being used to heat a specimen. For the initial experiments, the eddy current wand is hand-held and brought in close proximity to the fiberglass surface of the specimen, then the unit is activated, and a timer is monitored manually. For imaging with an infrared camera the heating is stopped after 5 seconds, for imaging with the thermochromic liquid crystals, 10 seconds of heating was required.

Figure 6 – Photograph of the ITS™ system used for heating the fiberglass specimens.

THEORY OF THERMAL EQUATIONS

A thin plate bonded to a backing material with heat flow is described by the equation:

$$\nabla^2 T(x,y,t) - \frac{F(x,y,t)}{wK} = \frac{1}{\kappa}\frac{\partial T(x,y,t)}{\partial t} \tag{1}$$

where F(x,y,t) is the flux into the second material, κ is the thermal diffusivity of the plate, w is the thickness of the plate and K is the thermal conductivity of the plate. If the diffusivity of the backing material is significantly lower than that of the plate, the flux quickly becomes nearly constant in time, and equation (1) reduces to

$$\nabla^2 T(x,y,t) - \frac{F(x,y)}{wK} = \frac{1}{\kappa}\frac{\partial T(x,y,t)}{\partial t} \tag{2}$$

The solution to equation (2) has been shown by Winfree, et. al.[7] to reduce to

$$\nabla^2 T_s(x,y) = \frac{F(x,y)}{wK} \tag{3}$$

Where Ts is the static or steady-state solution. If a delamination is present then the local temperature distribution is dominated by the flux variations caused by that delamination and the Laplacian of the local temperature distribution (equation (3)) gives an image of the flux variations in the plate, which should produce an image of the delamination.

To approximate the Laplacian and reduce the processing time a square filter was designed and the coefficients of the filter are then convolved with the thermal image to produce the Laplacian [7].

THEORY OF PRINCIPAL COMPONENT ANALYSIS

Principal Component Analysis (PCA) has been shown effective for reducing thermographic NDE data [8-12]. The algorithm used to perform the PCA is based on the decomposition of the thermal data into its principal components or eigenvectors

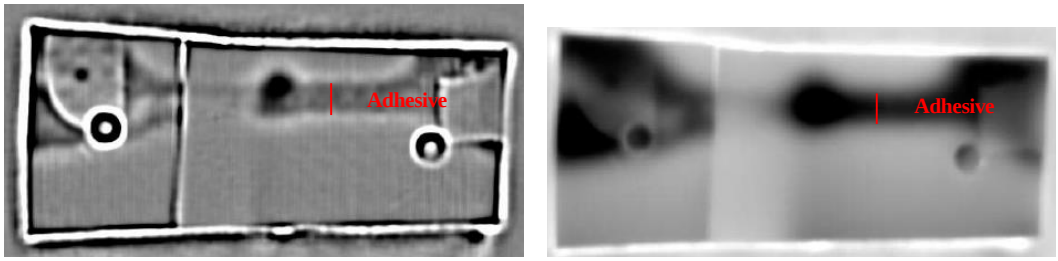
using Singular Value Decomposition (SVD). PCA is performed by first reformatting the three-dimensional thermal data into a two-dimensional array where the columns contain the spatial information and the rows contain the temporal information such that T(x,y,t) becomes A(n,m) where n = Nx * Ny and m = Nt. The matrix A is then adjusted by subtracting the mean along the time dimension, and decomposed to yield the eigenvalues and eigenvectors:

$$A = U\Gamma V^T \tag{4}$$

where U and V are orthogonal matrices whose columns form the eigenvectors of AAT and ATA respectively and Γ contains the singular values (the nonnegative square roots of the eigenvalues) of ATA. Since the columns of U corresponding to nonzero singular values form an orthogonal basis for the range space of A, the entire thermal data set can be described by this basis. Because thermal NDE signals are well behaved and slowly varying in time, the predominant temporal variations of the entire data set are usually contained in the first and second eigenvector. The PCA images are formed by calculating the dot product of the measured temperature response, pixel by pixel, with the eigenvectors of interest (usually the two associated with the largest eigenvalues). Defects in the material under investigation change the local temporal variation of the data and thus appear as either light or dark regions in the PCA images.

INFRARED CAMERA RESULTS

Immediately after heating with the eddy current heater, a 640 x 512 element FLIR SC6000 infrared (IR) camera is used to record the time/temperature history of the specimen during the cooling. The resulting data is processed using both PCA and the Laplacian technique described. Figure 7 (a) and (b) shows very consistent results which reveal the adhesive distribution of cut section #1 sample. It can be achieved with this technique using both data processing approaches. Also the measured width of adhesive bead is 8mm at which is marked in the Figure 7.



(a) (b)

Figure 7 – Cut section #1 after eddy current heating and imaged from the fiberglass surface with IR camera. Processed results using both (a) Laplacian and (b) PCA analysis.

THERMOCHROMIC LIQUID CRYSTALS

One technology that takes advantage of the effectiveness of thermal NDE and has proved particularly cost-effective in the some inspection scenarios are thermochromic liquid crystal (TLC) sheets [13]. TLC sheets are optically active mixtures of organic

chemicals that react to changes in temperature by changing color. TLC sheets show color by selectively reflecting incident white light. These typically turn from colorless (black against a black background) to red at a given temperature and, as the temperature increases pass through the other colors of the visible spectrum in sequence (orange, yellow, green, blue and violet) before turning colorless (black) again at a higher temperature still. Typically, the TLC sheets can be controlled at time of manufacture to have a pre-defined mid-green temperature and a specific full color change bandwidth. The TLC sheets can be obtained commercially in a number of different forms such as unsealed liquids, microencapsulated coating formulations and coated sheets. For the studies discussed here, the coated sheets were used exclusively. The coated sheets are available commercially and consist of a thin film of liquid crystals sandwiched between a transparent polymer (flexible) substrate and a black absorbing background.

To use the TLC sheets effectively for dis-bond detection it is necessary to induce a small temperature gradient between the bonded and dis-bonded regions of the parts being inspected. This can be done by actively injecting heat into the parts while observing the temperature changes that occur using the TLC sheets. For the TLC sheets to accurately measure variations in the temperature of the part, the sheets must be in good thermal contact with the part surface.

RESULTS FOR TLC SHEETS

To investigate the application of TLC sheets to the detection of dis-bonding in the specimens of interest, a TLC sheet of center temperature of 28ºC and range of 8ºC with 1ºC increment was placed over the specimen immediately after heating with the eddy current heater. The temperature of the specimen was observed during the cooling period and when what appeared to be a steady-state temperature distribution occurred, an image of the TLC sheet was recorded in the visible wavelengths with a digital camera. Figure 8 shows the typical results for the one of the specimens examined as a proof-of-concept. It shows the adhesive distribution of the bonded area. The width of the adhesive bead also could be measured by comparison with a known sample size in the image, if this is required for adhesive validation.

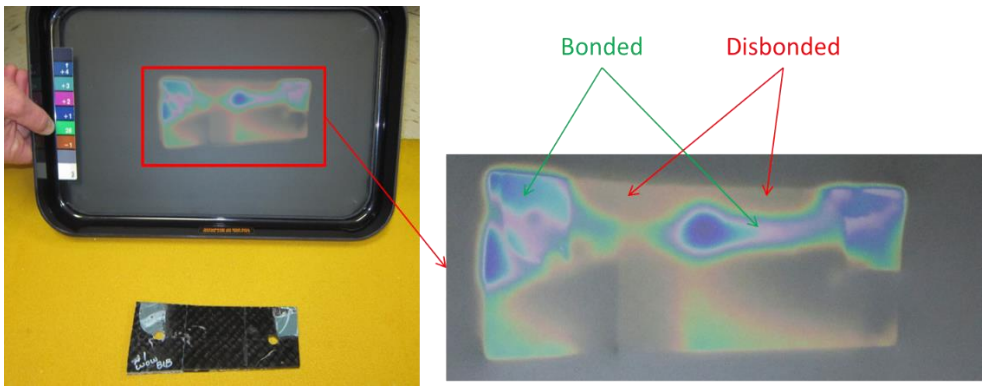


Figure 8 – Cut section #1 specimen after eddy current heating and imaged from the fiberglass surface by using TLC sheet.

CONCLUSION

A high level of accuracy on width and thickness measurements of the adhesive bead has been demonstrated by phased array ultrasound. This technology could be potentially used as quality validation of adhesive coverage. However, the data acquisition for a large-scale automotive part using this technology would take a large amount of time. The cost for a phased-array ultrasound system is from $50k to $90k, depending on different system configurations. Also, the inspection of composite-to-metal bonds in a manufacturing setting would require extensive training in data gathering, analysis, and interpretation.

Compared with ultrasonic NDE techniques, pulsed thermography provides reliable, rapid, and large scale contactless inspection. However, low cost pulsed thermography systems, without correspondingly low resolution, are still under development.

Induction heating with detection by an IR camera could provide very consistent results compare with pulsed thermography, but again, the IR camera is quite expensive and requires considerable training.

Instead of using an IR camera as the detector, TLC sheets have been demonstrated to have a number of advantages. A major advantage is the cost. The TLC sheets are quite inexpensive, costing approximately $25.00 (U.S.) for a 12in. by 12in. reusable sheet. Also, the inspection is rapid, typically taking only a few seconds. The sheets can either be applied to the inspection surface before or after the application of heat to the specimen. If the application of the sheet is done first, then a small amount of heat is applied through the sheet causing a temperature rise in both the sheet and the structure. Alternately, the application of heat into the part can be done first, then the part is quickly covered with a TLC sheet. If a delamination or disbond is present a temperature gradient will develop and be evident by non-uniform color changes in the TLC sheet. If desired, the results of the inspection can be recorded using a conventional camera, video or digital camera, and then archived for later reference.

Additionally, the test is totally nondestructive, as typical temperature changes of the surface are less than 5ºC, leaving the part under inspection undamaged. Further, the TLC sheets are very flexible (typical substrate is 0.1 mm Mylar) which allows conformance to many part shapes. The sheets can be cut to match the shape of specific parts. Finally, the TLC sheets provide clear indications of the size and location of the disbond areas in the part, which makes training and interpretation simple.

Over all, a robust and portable system consisting of induction heating as the excitation source and TLC sheet as the detector has been demonstrated. It provides reliable results, rapid inspection rate, non-sophisticated data interpretation for evaluation of bonds of fiberglass composite to metal, and is potentially feasible for automotive plant environments.

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